bridge (engineering)

A bridge is a structure designed to carry pedestrians or vehicles across such obstacles as ravines, rivers, or other roads or railroads. The earliest bridges may well have consisted of tree trunks or flat stones thrown across a stream--like the "clam" bridges of southeastern Cornwall or the "clapper" bridges of Dartmoor, which were the first beam bridges. Alternatively, the earliest types may have been primitive suspension spans formed of twisted bamboo or creepers hung across a stream, with their ends tied to tree trunks on either side; such bridges can still be seen in Africa and Asia. Little doubt exists that these were built long before the first masonry ARCH, even though both types were preceded by natural rock arches such as those at Ardeche in France or in Lexington, Va. In all three types of bridge--beam, arch, and suspension--the foundations must carry the full weight of the bridge and the traffic on it. The vital differences, however, are that arched bridges, by virtue of their shape, are in compression and thrust outward on their end supports or bearings, whereas the cables of a suspension bridge are in tension and exert a continual pull on their end anchorages.

EARLY BRIDGES OF NOTE

The finest early bridges were the semicircular masonry arches of the Romans, built during the 500 years of their supremacy. Some of these--such as the Alcantara bridge over the Tagus in Spain, with its tall, majestic spans of 30 m (98 ft)--are still standing after nearly 2,000 years. The most significant contributions of the Romans were the use of a natural cement called pozzolana that enabled them to make concrete below water in bridge foundations, and the use of timber cofferdams--made by driving piles around the site of a pier in midstream and then draining out the water inside--so that the ground could be excavated as necessary and the pier built on dry surface. The Ponte Sant' Angelo in Rome, which is still standing, was built on cofferdam foundations in the Tiber more than 1,800 years ago; most Roman bridges still standing, however, have piers built on solid rock.

By the Middle Ages the first ogival (pointed) arches were built in Europe; these arches resulted from Persian and Muslim influence. Bridges were often fortified to be used in defense of a city, such as the Pont Valentre at Cahors, France, which had arrow slits, machicolations, and protected stairways to the towers. To pay for the maintenance of many medieval bridges, tolls were levied not only on travelers crossing over but also on vessels passing under the bridge.

Toward the end of the 12th century, work began on two outstanding bridges, Old LONDON BRIDGE and the Pont St. Benezet at Avignon on the Rhone in the south of France. Begun in 1177 and completed ten years later, the Pont St. Benezet had 20 lofty elliptical arches, each spanning 30 m (98 ft). Unfortunately, little of the bridge remains today. The construction of the first stone bridge over the Thames in London, begun in 1176, presented even greater difficulties, for it was the first large bridge with masonry foundations to be built in a swiftly flowing river with a tidal range of 5 m (16 ft). The design consisted of 19 pointed arches on wide, protected piers and a drawbridge that served for defense and to let ships pass at high water. For more than 600 years the bridge supported a famous street of shops and houses flanking the narrow roadway. It even survived the Great Fire of London in 1666, which ravaged the northern end of the bridge. The street was not demolished until 1831, by which date a new bridge had been completed by Sir John RENNIE.

THE RENAISSANCE ERA

The next great bridge-building era occurred during the RENAISSANCE. An example of the unbounded confidence of the Renaissance was Leonardo da Vinci's offer to build a masonry arch bridge with a span of 240 m (787 ft) over the Golden Horn at Constantinople. In Florence, the Ponte Vecchio (c.1350), which still stands over the Arno, was eclipsed by the Santa Trinita bridge (1569) with its three "basket-handled" arches that had a rise-to-span ratio of only 1 to 7 instead of the usual 1 to 4. In 1588 Antonio da Ponte's design was accepted for the Rialto Bridge in Venice--a low circular arch that supports a 23-m-wide (75-ft) roadway lined with shops on a span of 27 m (89 ft) across the Grand Canal. To support the bridge in the soft alluvial soil of Venice, 6,000 wood piles were driven to a depth of 3.35 m (11 ft) beneath each abutment.

Other great examples of this age were the Pont Notre Dame (c.1500) and the Pont Neuf (1604), both masonry arch bridges over the Seine in Paris. These preceded the masterpieces of Jean Perronet (1708-94)--the Pont Neuilly over the Seine, the Pont de Sainte-Maxence over the Oise, and his last work, the Pont de la Concorde (1791).

BRIDGES OF THE 18TH AND 19TH CENTURIES

During the 18th and 19th centuries a wide variety of timber truss bridges were built in North America, including the Colossus bridge of 104-m (340-ft) span over the Schuylkill River. In the late 18th century another innovation began with the building of the world's first all-iron bridge, the semicircular arch of 30-m (100-ft) span at Coalbrookdale over the River Severn in England.

In the 19th century, as more and more railroads were built, cast iron was superseded by wrought iron, because the latter was malleable, ductile, much stronger, and could be riveted instead of bolted. In 1826, Thomas TELFORD completed the 177-m (580-ft) span Menai suspension bridge, which was supported by cables of wrought-iron links; it carried two lanes of roadway traffic over the straits. In addition, Robert STEPHENSON's Britannia Railway Bridge, also across the Menai Straits, was opened in 1850. It had four continuous spans, two of 70 m (230 ft) and two of 140 m (460 ft), consisting of wrought-iron tubes of rectangular cross section, through which the trains ran. This was the prototype of the modern steel box girders. The main difference today is that the traffic is carried on a roadway above the tubes or boxes instead of through them. Only a few years later, in 1859, I. K. BRUNEL completed his last and greatest project, the Royal Albert bridge at Saltash, England, with its two spans of 142 m (465 ft), each carrying one broad-gauge railway over the Tamar estuary.

Before the end of the 19th century the mass production of mild steel plates and sections, with an ultimate strength of about 4.1 kilonewtons (kN) per sq m (30 tons per sq in) in both tension and compression, led to their use in building bridges. The first large bridge in the world to be built of steel was the St. Louis bridge (1874) over the Mississippi River. Designed by James B. EADS, it had three arch spans of more that 152 m (500 ft) each. This was followed by the construction (1869-83) of the BROOKLYN BRIDGE, a suspension bridge of 486-m (1,595-ft) span traversing the East River and linking Brooklyn with Manhattan. Designed by John A. ROEBLING, the bridge is nearly half again as long as any bridge previously built; it has six lanes for vehicular traffic and a footpath. The four main cables each comprise parallel wires of galvanized cast steel 4.82 mm (0.19 in) thick, with an ultimate strength of 9.85 kN per sq m (71.5 tons per sq in). The cables were spun in place by a method that has subsequently been used in every large suspension bridge built in the United States. To prevent failure brought on by oscillations built up in the deck by wind or traffic, steel-stiffening trusses were incorporated in the deck over the entire length of the bridge.

The next major advance was the Forth Railway bridge (1882-90), with two cantilever spans of 521 m (1,710 ft) each, which carries a double railway track over the Forth Estuary at South Queensferry, Scotland. Unlike the Britannia and Royal Albert bridges, where the spans were floated out and hoisted up, all the steelwork of the Forth bridge was cantilevered out at the site from the main piers and riveted in place.

NEW CONSTRUCTION TECHNIQUES

This period also saw the building of the first modern types of movable bridges, such as the bascule bridge, lift bridge, and swinging drawbridge. The largest bascule bridge to date--in which the opening spans swing upward as in the Tower Bridge in London--is the railway bridge built in 1941 at Sault Ste. Marie, Michigan. The bridge has an opening of 102 m (335 ft). In lift bridges, the opening span remains horizontal and is counterweighted at the ends and lifted vertically. The lifting span of the Arthur Kill bridge (1959) at Elizabeth, N.J., has a length of 170 m (558 ft). Swinging draw-bridges have swing spans that remain horizontal and are usually swung round on a central pivot or pin; thus they cause more obstruction to river traffic than do other movable bridges. The longest swing bridge yet built (1965) is that at al Firdan over the Suez Canal in Egypt; it has two arms that swing round on turntables at each end, giving an opening of 168 m (552 ft). Floating bridges have been built since the 1st millennium BC, but their life is short and they require much maintenance. The well-known BAILEY BRIDGE was a standardized steel-latticed truss, designed to make quick replacements for bridges destroyed in wartime.

Various kinds of bridge foundations are also used. Cofferdams are still used when the ground is suitable, and the use of steel-sheet piling has enabled much larger and deeper foundations to be laid. If the ground is too hard or too soft for piling, however, caissons or wells are used and are either sunk by open grabbing or, as in the Royal Albert bridge at Saltash, by means of compressed air. At Saltash, a wrought-iron cylinder 11 m (36 ft) in diameter was sunk to the rock at a depth of 26 m (85 ft) in midstream. The water was expelled from the working chamber at the bottom by pumping in compressed air; workmen entered through an air lock and excavated the ground, so that the cylinder sank until hard rock was reached; then the caisson was plugged with concrete, and the piers were built up to the necessary height.

Compressed air cannot be used in foundations deeper than about 37 m (120 ft) because at that depth the pressure would be 3.6 N/sq m (52 lb/sq in), which is high enough to cause the BENDS (caisson disease) in workmen. For very large foundations, reinforced concrete monoliths can be sunk instead of steel caissons, as was done for the

Howrah bridge in Calcutta, where the monoliths measured 55 by 25 m (180 by 82 ft) in plan and were sunk to a depth of 31 m (102 ft). The latest trend is away from pneumatic caissons, turning instead to the use of piles that may be 0.9 m (3ft) or more in diameter and stressed concrete up to 6 m (20 ft) in diameter that can be driven to depths of more than 30 m (98 ft).

THE 20TH CENTURY: CONCRETE AND STEEL

The 20th century ushered in the building of bridges using reinforced concrete. Concrete resists compressive forces, and the steel reinforcement resists tensile stresses that concrete alone would be unable to withstand. The first spans to be built of reinforced concrete were arches, a notable one being Francois Hennebique's Pont de Chatellerault (1898), with a span of 52 m (171 ft). In 1905, Robert Maillart built the first of his three-hinged arches, the Tavanasa bridge over the Rhine in Switzerland. He next built the Schwandbach bridge (1924), which was curved in plan and had a span of 34 m (112 ft) across a deep ravine. Eugene Freyssinet's masterpiece was the Pont Albert Louppe (1930) over the River Elorn in Brittany; it has three arched spans of 172 m (564 ft) each. Another major work was the Sando bridge (1942) in Sweden, with a span of 264 m (866 ft) and a low arch with a rise of only 40 m (131 ft) at the center. The Gladesville Bridge (1964) in Sydney, New South Wales, has an even longer span--305 m (1,000 ft) of reinforced concrete that carries a 22-m (72-ft) wide roadway and two footpaths supported on columns above its low, graceful arch.

The process of prestressing concrete first developed by Freyssinet consists of putting the concrete into a state of compression by tensioning steel wires or bars that pass through it; this system was universally adopted after World War II. At the same time, marked improvements in concrete technology led to its allowable compression strength being doubled to 0.2 kN/sq m (3,000 lbs/sq in). These improvements enabled designers to save approximately one-third of the volume of concrete and three-quarters of the weight of steel reinforcement over what previously had to be used. Prestressed concrete bridges thus became strongly competitive and have been widely adopted for spans up to 180 m (600 ft) or even 305 m (1,000 ft) if the bridges are braced by cables. For short spans, simple beams can be used, as is the case for the two Pontchartrain bridges in Louisiana (1958 and 1969), which have 2,170 and 2,174 spans, respectively, each 17 m (56 ft) long. As the spans become longer, they can be made continuous, as was done in the Moscow River bridge (1957) in the USSR. This is a double-decked bridge carrying roadway traffic above and railway traffic below; it has two spans of 44 m (144 ft) each and one span of 148 m (485 ft). One of the longest prestressed concrete cantilever bridges is the Bendorf bridge (1964) in Koblenz, Germany, which has a clear span of 208 m (682 ft).

Various other types of prestressed concrete bridges exist: tied arch, lattice truss, box girder, multiple suspension, and cable braced. When they were constructed in 1970, the longest multiple suspension bridge was the Save River bridge in Mozambique, with two spans of 100 m (328 ft) each and three of 210 m (689 ft) each. The longest cable-braced bridge is the Wadi Kuf bridge in Libya, which has a single span of 300 m (983 ft).

After prestressed concrete, steel is the material most widely used for bridge construction. Research has been concentrated on production of high tensile steel, which can be used at a much higher working stress than mild steel and yet is still suitable for fabrication by flame-cutting and electric arc welding. Today, riveting has been superseded by welding in the shops during fabrication and by the use of friction grip bolts for making on-site connections.

Over the years bridges have failed, mostly during construction, and today much effort is being devoted to ensuring the safety of bridges during erection and, above all, to guaranteeing the safety of the personnel on site. A few of the most tragic failures during erection were the collapse of the cantilever of the Quebec bridge (1907) due to buckling of the main chords, in which 74 men died; and the collapse of the suspended span of the same bridge in 1916 as it was being lifted into place from the water, causing 13 more deaths. More recently, the failure of a large steel box girder during the erection (1970) of the West Gate bridge in Melbourne killed 35 men. The principal causes of other failures that have taken place after completion of the bridge have been high winds, which blew down 13 of the high level spans of the Tay bridge, Scotland, with a train on them, in 1879; aerodynamic oscillations, which brought down the Tacoma Narrows bridge in 1940; brittle fractures of steelwork, earthquakes, floods, and the impact of a ship on the bridge piers.

In the 20th century the United States has led the way in building great suspension bridges with spans from 610 m (2,000 ft) to more than 1,219 m (4,000 ft). The greatest of these, the VERRAZANO-NARROWS BRIDGE (1964) at the entrance to New York Harbor, carries a double-deck roadway for 12 lanes of traffic and has steel towers 207 m (680 ft) high. The four main cables, each 0.9 m (3 ft) in diameter, contain 229,300 km (142,200 mi) of wire. The Sydney Harbour bridge in New South Wales was opened in 1932; it has a 503-m (1,650-ft) span and carries four

interurban railway tracks, a 17-m-wide (56-ft) roadway and two footpaths. Other major suspension bridges, were completed in the United Kingdom. The Forth Road bridge (1967) and the Severn bridge (1966) both have spans exceeding 914 m (3,000 ft); the 1,410-m (4,626-ft) main span of the Humber bridge, near Hull England, was the longest in the world when completed in 1981. The Bosporus bridge, of 1,073-m (3,520-ft) span, opened at Istanbul in 1973, created the first road link between Europe and Asia since Xerxes' bridge of boats in 500 BC. Projects for the future include a bridge over the Messina Straits, where the 122-m (400-ft) depth of water poses a major problem.

The newest bridge design, the cable-stayed bridge, is suspended by cables that run directly down to the roadway from centrally-positioned towers. Because they are less costly than conventional suspension bridges, cable-stayed bridges have been built, largely in Europe, for spans up to about 700 m (2,000 ft). The dynamics of these bridges, however, create special stresses on the cables, and improved technologies must be used to prevent cable corrosion.

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